Atmospheric lee waves and their possible influence on the sea surface

Lucien Wald, Dimitri Georgopoulos

83-A-14

ATMOSPHERIC LEE WAVES IN THE AEGEAN SEA AND THEIR POSSIBLE INFLUENCE ON THE SEA SURFACE

(Research Note)

LUCIEN WALD

Centre de Télédétection et d'Analyse des Milieux Naturels, Ecole Nationale Supérieure des Mines de Paris, Sophia-Antipolis, 06565 Valbonne Cedex, France

and

DIMITRI GEORGOPOULOS

Institute of Oceanographic and Fisheries Research, Aghios Kosmas, Hellinikon, Athens, Greece

(Received in final form 11 January, 1984)

Abstract. Unusual satellite images of the Aegean Sea, in both the visible and infrared ranges, are discussed. Alternating bright and dark features downwind of islands suggest the presence of atmospheric lee waves. However, close examination of these features indicates that the observed signal is likely the signature of the influence of the lee waves on the sea surface rather than the signature of the lee waves themselves through atmospheric effects.

1. Satellite Observations on April 7 and 8, 1981

Satellite observations of the Aegean Sea were obtained from NOAA 6 on April 7, 1981, at 0651 GMT and on April 8, 0636 GMT, in both the infrared and visible channels. An infrared image from NOAA 6 was also available on April 7, 1817 GMT.

In Figures 1 and 2 are presented the infrared (Figure 1) and the visible (Figure 2) images obtained on the morning of April 7. The infrared image of April 7, 1817 GMT, is shown in Figure 3. In these photographs, the clearer the shade, the colder the temperature (Figures 1 and 3) and the greater the albedo (Figure 2).

The AVHRR sensor aboard NOAA 6 has five channels ranging from visible (channel 1) to thermal infrared (channel 5). The first three channels give similar results (Figure 2), a measure of the energy reflected by the surface of the sea, and consequently an indication of sea state roughness.

In all channels, one can see the alternating clear and dark bands behind the Cyclades and Sporades Islands (Figure 4). This pattern is very regular and is quite stationary over 24 hr. The mean distance between two consecutive bands is 9.5 km, with a rms of 4 km, and the length of these bands is about 30–40 km.

Such a pattern is very characteristic of lee waves (Cruette, 1973). Existence of winds of 8–10 m s^{-1} blowing from the NNW against the rocky islands during these two days supports this idea. The structure and the shape of the wave may vary critically, depending upon the vertical profiles of wind velocity, air temperature and air humidity (Förchtgott, 1949; Kuettner, 1958; WMO, 1960).

Boundary-Layer Meteorology **28** (1984) 309–315. 0006–8314/84/0283–0309$01.05.

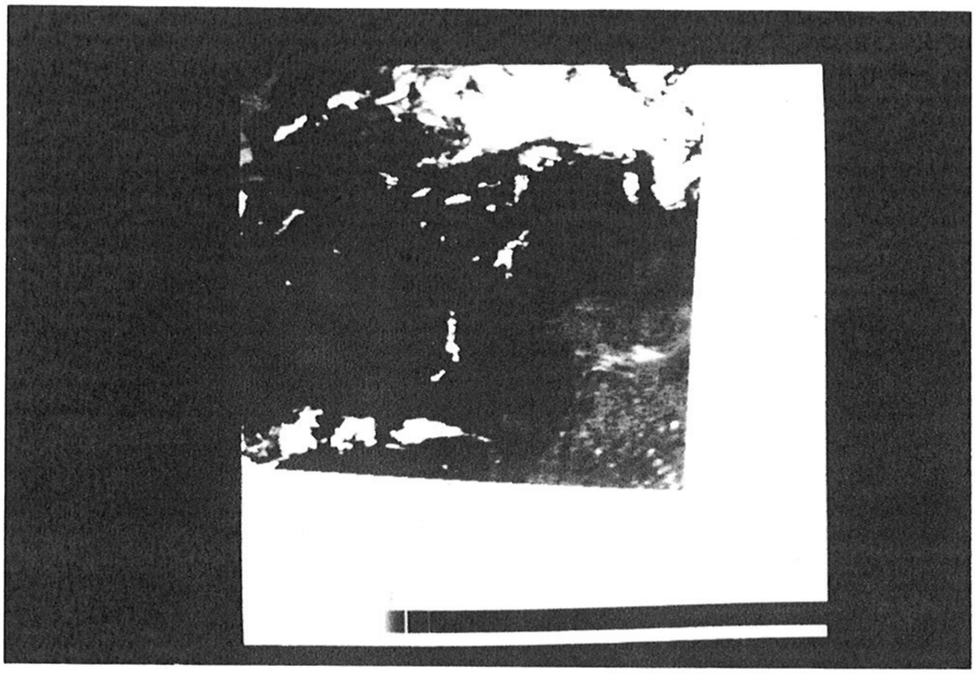

Fig. 1. Infrared image of the Aegean Sea from NOAA 6, taken on April 7, 1981, at 0651 GMT. The brighter the shade, the lower the temperature.

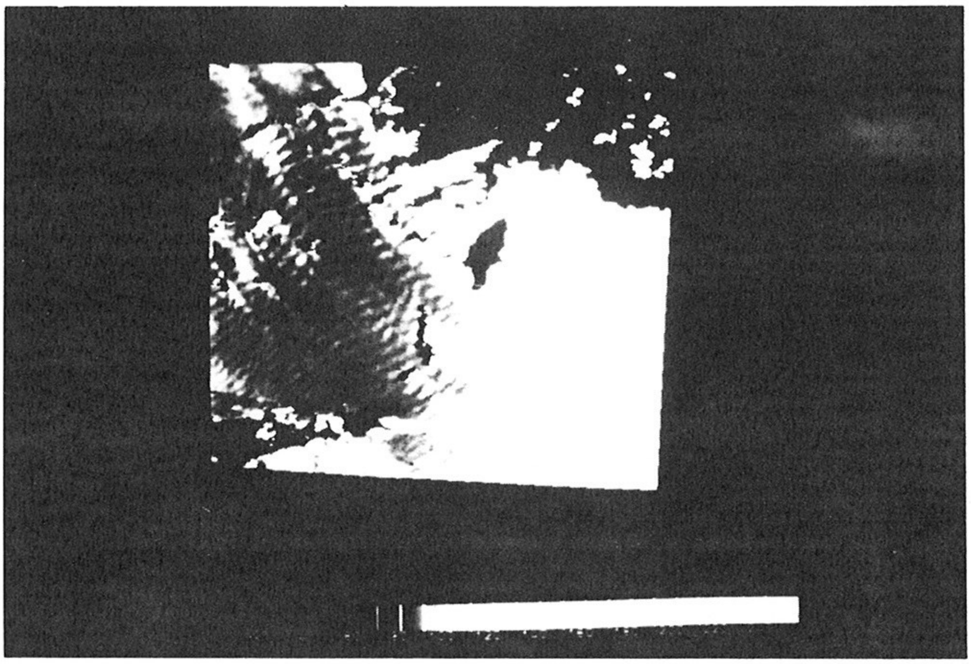

Fig. 2. Same as Figure 1, but for visible range. The brighter the shade, the higher the albedo.

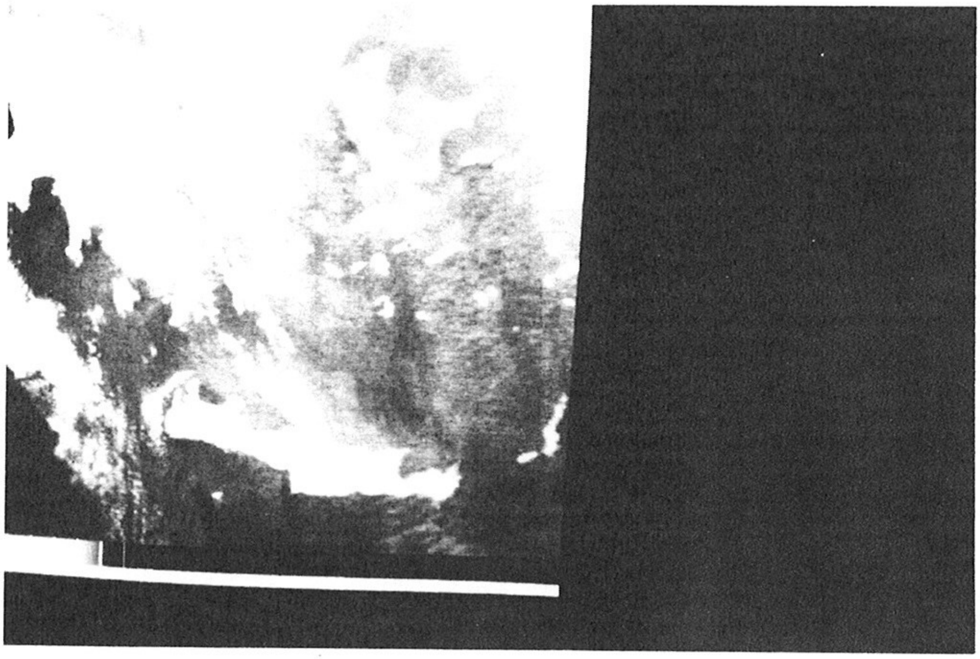

Fig. 3. Same as Figure 1, but for April 7, at 1817 GMT.

Cruette (1976) points out that leewaves are generally associated with the presence of a stable atmospheric layer at intermediate height, and favorable wind speed, direction and profile. Soundings of the atmosphere are only available for Athens and Heraklion (Crete). While aware of the great variability of the wind over the Aegean Sea induced by the numerous rocky islands, the authors expect the bulk features observed in these soundings to be applicable to this Sea. The wind was blowing from the NNW (320–360° in Heraklion), perpendicular to the islands under concern, with increasing wind speed from the surface (8–10 m s^{-1}) to the height 10 km. These soundings also show that the atmosphere was stable. All these features are very favorable to the existence of lee waves, which can be depicted as a regular sinusoïd downwind of the island (Figure 5).

It has been established that the wavelength must increase linearly with the mean speed in the troposphere but recent work (Cruette, 1976) suggests that the coefficients of the relationship may vary from case to case. However, this relationship is of the form:

$$\lambda = aV + b$$

where λ is the wavelength expressed in km and V is the mean wind speed in m s^{-1}. Based on the pressure charts of the German Meteorological Office, the mean wind speed is assumed to be 15 m s^{-1}, so that the computed wavelength is, for the different values of a and b:

(Corby, 1957) $a = 0.587$; $b = -2.8$; $\lambda = 6.0$ km
(Georgii, 1967) $a = 0.67$; $b = 0.0$; $\lambda = 10.0$ km
(Cruette, 1976) $a = 0.49$; $b = 1.9$; $\lambda = 9.4$ km.

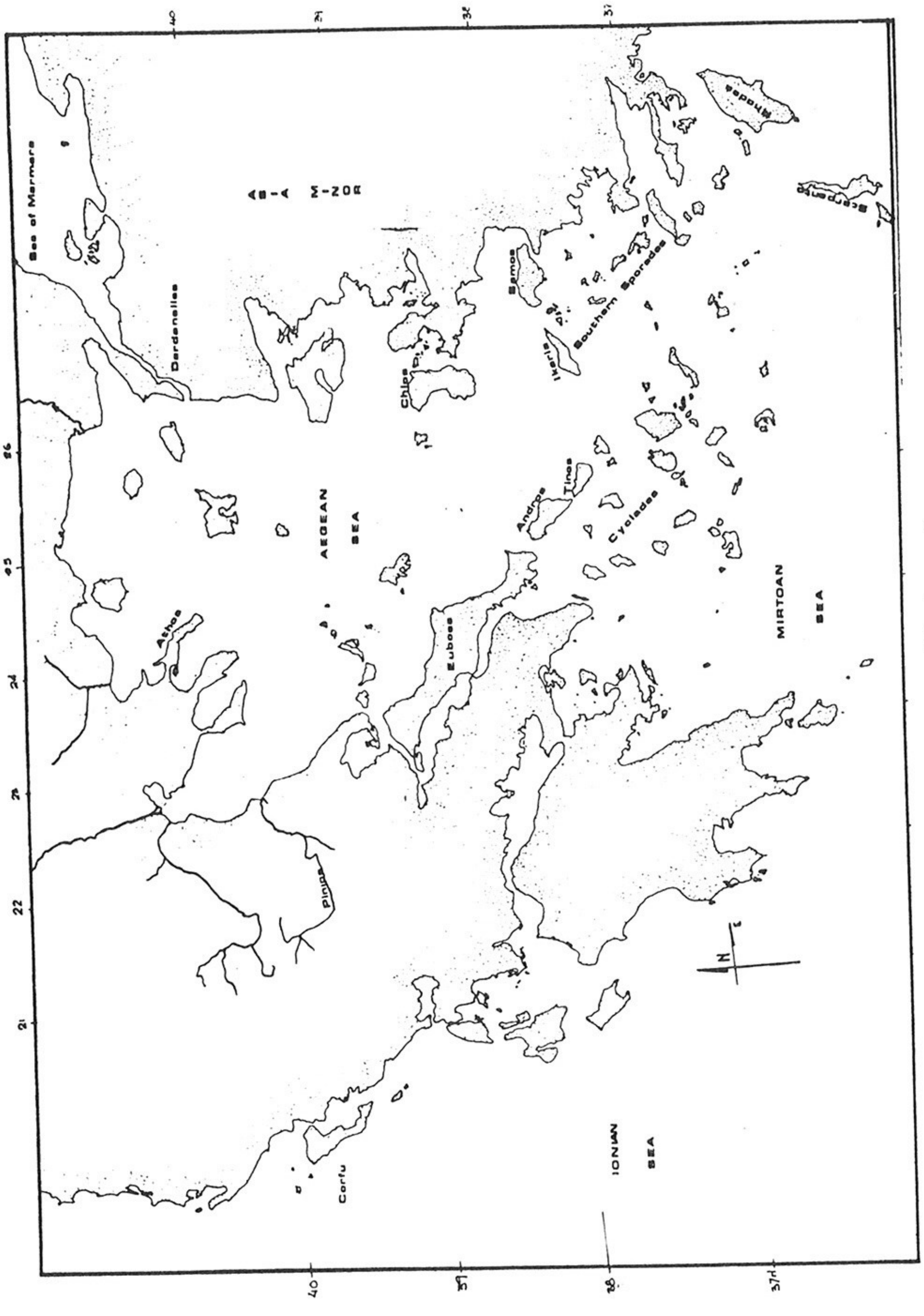

Fig. 4. Map of the Aegean Sea.

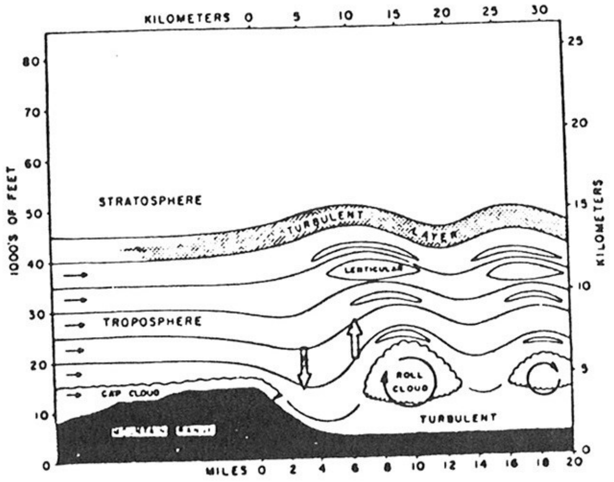

Fig. 5. Schematic diagram of mountain wave flow. After Kuettner (1958).

These values are in agreement with the observed wavelength (9.5 km).

The crests of the lee wave are usually surrounded by clouds or mist of high reflectance and thus one can observe patterns of low and high albedo. The crests are often colder than the sea temperature, but at times, in case of a temperature inversion in the lower atmosphere, the mist can be warmer than the sea. These are common features (Cruette, 1976) and the existence of atmospheric lee waves in this region is well known and is not the point of the present note.

These particular images display some unusual features which suggest that the observed signal does not come from the atmospheric layer but rather from the sea surface influenced by the lee wave. These features are now presented.

First of all, the pattern of clear and dark stripes never crosses an island, which may indicate that the signal is not of atmospheric origin.

According to Figure 5, a trough is found downwind and close to the island. If the signal were of atmospheric origin, one would expect a low albedo. But one observes a high albedo.

Examination of both atmosphere soundings and satellite imagery made by D. Cruette and A. Noyalet (personal communications) reveals that the existence of clouds during these days was highly unprobable; even if they occurred, the temperature of the cloud tops would be less than 5 °C and thus would be detected by infrared imagery (Figure 1) whereas the temperature change between cold and warm stripes is of order of 0.4 °C, the mean temperature being 14 °C.

From the above remarks, one can conclude that the observed signal from the lee wave is not the expected one. There is no cloud or mist, so that the signal is not of atmospheric origin. The authors suggest that the discrepancy can be explained in the following way. The signal comes from the sea surface itself and expresses the influence of the lee wave upon the sea surface.

2. Discussion

In the images taken on the morning (0830 and 0815 True Solar Time) of April 7 and 8, dark strips occur in the same place in both visible and infrared ranges. According to the computations of Wald and Monget (1983) about glitter reflectance as a function of sea state, sun and observer geometry, one concludes that in this case, the darker the shade, the rougher the sea (Figure 2). These strips of rough sea occur below the crests of the lee wave, under which vortex (rotors) are found and very severe turbulence occurs (Figure 5).

Thus in the morning one observes a regular pattern of warm and rough sea (dark strips) and cold and calm sea (bright strips). The thermal difference is of order of 0.4 °C. However, in the infrared imagery obtained on April 7, 1817 GMT, one observes cold strips where warm strips occurred in the morning and warm strips in place of the cold strips (Figure 3). But the thermal difference is weaker, being less than 0.2 °C.

The authors suggest the following explanation. In the early morning, the sea surface temperature is lower than the temperature at 1 m depth, because of night-time cooling, the thermal difference being of order of a few tenths of a degree. Under the lee wave crests, strong turbulence causes the mixing of the sea surface layer, leading to a local heating of the skin of the sea, sensed by the satellite. Then the solar energy warms the sea, but the heating of the calm strips is stronger than the heating of the rough strips since for the latter, a greater depth is involved. Thus at the end of the day, the calm strips are the warmest but the thermal difference is weak.

3. Conclusion

Observations of a lee wave have been presented in this note. Some unusual features appearing in satellite imagery suggest that the satellite does not sense the atmospheric effects usually accompanying a lee wave (clouds) but the sea surface. The sea surface characteristics are modified by the lee wave, the influence of which is expressed in local changes in both temperature and surface roughness.

Such an observation was recently reported by M. Champagne-Philippe (personnal communication). During the ?Donde Va? experiment made in October 1983, while flying over the Alboran Sea, her aircraft encountered a lee wave. She observed that while on a crest of the wave (strong turbulence), the sea below the plane was rough; when in a trough, on the other hand, the sea was quieter, in agreement with the observations presented in this note.

Acknowledgements

D. Georgopoulos visited Ecole des Mines in 1981, supported by an UNESCO fellowship. He thanks J. M. Monget and his staff for their hospitality and also G. Fredj for his help.

The satellite data were kindly provided by the Centre de Météorologie Spatiale in Lannion.

The authors deeply thank D. Cruette, M. Champagne-Philippe, P. Y. Deschamps, and A. Noyalet for their helpful discussions and criticisms.

References

Corby, G. A.: 1957, A Preliminary Study of Atmospheric Waves Using Radiosonde Data', *Quart. J. Roy. Meteorol.* **83**, 49–60.

Cruette, D.: 1973, 'Etude expérimentale des perturbations de relief à l'aide de photographies de satellites et de mesures en avion', Thèse d'Etat, Université de Paris VI.

Cruette, D.: 1976, 'Experimental Study of the Moutain Lee Waves by Means of Satellite Photographs and Aircraft Measurements', *Tellus* **28**, 499–523.

Förchtgott, J.: 1949, 'Wave Streaming in the Lee of Moutain Ridges', *Bull. Met. Czech., Prague* **3**, 49.

Georgii, W.: 1967, *Kinematik der Leewellen-Strömung*, Deutsche Versuchsantalt für Luft und Raumfahrt, DLR FB 67-20.

Kuettner, J: 1958, 'The Rotor Flow in the Lee of Mountains', *Schweizer Aero-Revue, Bern* **33**, 208–215.

Wald, L. and Monget, J. M.: 1983, 'Remote Sensing of the Sea State Using the 0.8–1.1 Micron Spectral Band', *Int. J. Remote Sens.* **4**, 433–446.

WMO: 1960, *The Air Flow over Mountains*, by P. Queney (chairman), G. A. Corby, N. Gerbier, H. Koschmieder, J. Zierep. WMO Tech. Note No. 34, Geneva.